CHEMICAL SPECIES SUPPRESSION FOR MRI IMAGING USING SPIRAL TRAJECTORIES WITH OFF-RESONANCE CORRECTION

BACKGROUND OF THE INVENTION

[0001]   The present invention relates to a method of fat suppression in MRI imaging and more particularly to a method of fat suppression using Dixon techniques with spiral trajectories.

[0002]   Off-resonance effects (e.g., field inhomogeneity, susceptibility, chemical shift) cause artifacts in magnetic resonance imaging (MRI). The artifacts appear as positional shifts along the readout direction in rectilinearly sampled acquisitions. Usually, they are insignificant, because of short readout times, in normal spin echo (SE) and gradient echo (GRE) sequences. However, off-resonance artifacts sometimes appear as severe geometric distortion because of the relatively long readout time in echo planar imaging (EPI).

[0003]   Over the past decade, spiral imaging techniques have gained in popularity due to their short scan time and insensitivity to flow artifacts. However, off-resonance effects (e.g., ~3.5ppm shift between fat and water protons) cause blurring artifacts in the reconstructed image. Most spiral off-resonance correction methods proposed to date are difficult to apply to correct for blurring artifacts due to the fat signals since the fat-water shift is typically much greater than that due to B0 inhomogeneities across the field of view (FOV). As such, off resonance artifacts remain one of the main disadvantages of spiral imaging.

[0004]   Currently, off-resonance artifacts are most commonly avoided by use of spatially and spectrally selective radio-frequency (RF) excitation pulses (SPSP pulses) since they excite only water spins, thereby eliminating the off-resonance fat signal and hence avoid artifact generation. Yet, SPSP pulses usually take a significant fraction of the TR of a spiral sequence, particularly when a sharp transition band is designed between two chemical shift frequencies. The time duration of SPSP pulses is sometimes even equivalent to the spiral readout duration. This can be considered as one of the current limitations to reducing scan time in spiral imaging, and thus, alternative approaches to fat-water separation in spiral imaging are required.

[0005]   Excitation of only water spins could be achieved through application of chemical shift presaturation pulses (e.g., CHESS pulses) prior to normal spatially selective

excitation. However, the effectiveness of these frequency selective RF excitation pulses is dependent on the main magnetic field (B_0) inhomogeneity.

[0006]   Alternatively, Dixon techniques have primarily been investigated for water-fat decomposition in rectilinear sampling schemes. In the original Dixon technique, water and fat images were generated by either addition or subtraction of the "in-phase" and "out-of-phase" data sets. Water and fat separation is unequivocal using this technique when magnetic field inhomogeneity is negligible over the scanned object. However, when B_0 inhomogeneity cannot be neglected, the original Dixon technique fails to accurately decompose water and fat signals. Therefore, modified Dixon techniques using three data sets (i.e., three-point Dixon (3PD) technique) or four data sets were developed to correct for B_0 inhomogeneity off-resonance effects and microscopic susceptibility dephasing. New versions of the Dixon technique use two data sets with B_0 inhomogeneity off-resonance correction (i.e., two-point Dixon (2PD) technique). The water-fat decomposition performance is almost equivalent to that of the 3PD technique although off-resonance frequency estimation of this technique would be unstable for voxels with nearly equal water and fat signal intensities. The advantage of these multiple-point Dixon techniques over spectrally excited RF pulses is that water-fat separation can be achieved even in the presence of B_0 inhomogeneity. This advantage is of notable importance because neither tissue-induced local magnetic field inhomogeneity nor external applied magnetic field inhomogeneity can be completely removed by shimming.

BRIEF DESCRIPTION OF THE DRAWINGS

[0007]   The invention may take form in certain components and structures, preferred embodiments of which will be illustrated in the accompanying drawings wherein:

[0008]   **Fig. 1.** is a simplified sequence diagram of the spiral three-point Dixon (spiral 3PD) technique;

[0009]   **Fig. 2.** illustrates an example of D_{local}-f_j plots that have two local minima;

[0010]   **Fig. 3.** illustrates a selection process of the correct local off-resonance frequency using a region growing algorithm;

[0011]   **Fig. 4.** is a simplified sequence diagram of the spiral two-point Dixon (spiral 2PD) technique;

[0012]   **Fig. 5.** illustrates water and fat magnetization vectors in the transverse plane at the onset of the spiral gradient in the spiral 2PD technique; and

[0013]   **Fig. 6.** illustrates variable density spiral (VDS) trajectories for Dixon techniques with one acquisition.

DETAILED DESCRIPTION OF THE INVENTION

[0017]   It is to be understood that the specific devices and processes illustrated in the attached drawings, and described in the following specification are simply exemplary embodiments of the inventive concepts defined in the appended claims. Hence, specific dimensions and other physical characteristics relating to the embodiments disclosed herein are not to be considered as limiting.

[0018]   The long readout time of spiral trajectories leads to off-resonance signals that blur into neighboring pixels; spins from multiple off-resonance frequencies can all contribute to the voxel signal. However, it can generally be assumed that B_0 inhomogeneity is smoothly varying across the FOV (this assumption will be referred to as 'assumption (i)'). Thus, the average off-resonance frequency in any pixel is usually close to the true local B_0 field strength. This concept is exploited in the conventional method to create an off-resonance frequency map in spiral imaging, in which the phase difference is taken between two images (with different TE's) even though both images are already blurred by off-resonance effects.

[0019]   In addition to assumption (i), it is also assumed that: (ii) Only two chemical shift species, i.e. water and fat, are considered, and their spectra are both sufficiently narrow so that little spectral overlap occurs, and, (iii) Signal intensity differences due to T2* decay among data sets with different TE's are negligible. While water and fat are used as the two chemical species in the examples provided herein, it should be appreciated that the invention can be applicable to any other two suitable chemical species.

Spiral 3PD technique

[0020]   Suppose that three k-space data sets with TE differences (ΔTE (s)) are acquired using a normal spatially selective RF pulse for each TR (Fig.1). As shown, the TE difference between the first and the second acquisitions and that between the second and the third acquisitions are set to equal (ΔTE).

[0021]   The signals at each pixel in the reconstructed images (S_0, S_1 and S_2) from these data sets can be expressed as:

$$S_0 = W' + F' \qquad\qquad [1]$$

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$$S_1 = (W' + F' \exp(i\phi_{fat})) \exp(i\phi) \qquad [2]$$

$$S_2 = (W' + F' \exp(i2\phi_{fat})) \exp(i2\phi) \qquad [3]$$

where W' represent water signals blurred by local B_0 inhomogeneity off-resonance frequency f (Hz), F' are fat signals blurred by local B_0 inhomogeneity and chemical-shift off-resonance frequencies $f + f_{fat}$ (Hz), and ϕ and ϕ_{fat} are the phase shifts due to B_0 inhomogeneity and chemical-shift off-resonance effects during ΔTE. That is,

$$\phi = 2\pi f \cdot \Delta TE, \qquad [4]$$

$$\phi_{fat} = 2\pi f_{fat} \cdot \Delta TE. \qquad [5]$$

respectively.

[0022]   A quadratic equation with respect to $\exp(i\phi)$ can be derived from Eqs.[1-3] to provide an estimate of the frequency field map:

$$\exp(i\phi) = \frac{S_1(\exp(i\phi_{fat}) + 1) \pm \sqrt{S_1^2(\exp(i\phi_{fat}) + 1)^2 - 4S_0 S_2 \exp(i\phi_{fat})}}{2S_0 \exp(i\phi_{fat})} \qquad [6]$$

In practice, it is difficult to select one appropriate root from the two roots given by Eq. [6]. Moreover, at the pixels where image SNR is low, both roots of Eq.[6] may be inaccurate.

[0023]   Alternatively, several different predetermined frequencies f_j (Hz) for a sufficiently wide frequency range are substituted into Eqs.[1-3], and W' and F' are solved for each frequency f_j. The calculated W' and F' (Eqs.[7,8]) are compared with the observed signals, S_0, S_1 and S_2. The objective is to find the f_j that provides the best fit of calculated W' and F' to the observed signals. Given a frequency f_j, W' and F' can be solved from any two equations of Eqs.[1-3]. To make signal contributions from S_0, S_1 and S_2 equal to the calculated W' and F', they are computed as follows:

$$\overline{F}'_j = \frac{1}{3}(F'_{01,j} + F'_{12,j} + F'_{20,j}) \qquad [7]$$

$$\overline{W}'_j = \frac{S_0 + S_1 + S_2 - \overline{F}'_j (1 + \exp(i(\phi_j + \phi_{fat})) + \exp(i2(\phi_j + \phi_{fat})))}{1 + \exp(i\phi_j) + \exp(i2\phi_j)} \qquad [8]$$

where

$$F'_{01,j} = \frac{\exp(i2\phi_j)S_0 - \exp(i\phi_j)S_1}{\exp(i2\phi_j)(1 - \exp(i\phi_{fat}))} \qquad (F' \text{ derived from Eqs.}[1, 2]),$$

$$F'_{12,j} = \frac{\exp(i\phi_j)S_1 - S_2}{\exp(i2\phi_j)\exp(i\phi_{fat})(1 - \exp(i\phi_{fat}))} \qquad (F' \text{ derived from Eqs.}[2, 3]),$$

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$$F'_{20,j} = \frac{\exp(i2\phi_j)S_0 - S_2}{\exp(i2\phi_j)(1 - \exp(i2\phi_{fat}))} \qquad (F' \text{ derived from Eqs.[3, 1])},$$

$$\phi_j = 2\pi f_j \cdot \Delta TE.$$

At each pixel, variation between the observed and calculated signals, D_{pixel} (Eq.[9]) will be minimized at $j = l$ if the frequency f_l is the closest to the actual B_0 inhomogeneity off-resonance frequency out of all the test frequencies f_j.

$$D_{pixel} = |S_0 - (\overline{W}'_j + \overline{F}'_j)| + |S_1 - (\overline{W}'_j + \overline{F}'_j \exp(i\phi_{fat}))\exp(i\phi_j)|$$

$$+ |S_2 - (\overline{W}'_j + \overline{F}'_j \exp(i2\phi_{fat}))\exp(i2\phi_j)| \qquad [9]$$

In practice, D_{pixel} may not take the minimum value when $j = l$ at those pixels where image SNR is low. To reduce the errors from noise, a small multi-pixel window is set about each location and the summation of D_{pixel} within the window is measured:

$$D_{local} = \sum_{window} D_{pixel} \qquad [10]$$

[0024]   Even if noise effects are completely eliminated, a plot of D_{local} with respect to f_j sometimes takes two local minima as shown in Fig.2. This can be understood since Eq.[6] gives two roots. Since both roots in Eq.[6] satisfy Eqs.[1-3], D_{local} may not be the actual local field strength. To select a correct frequency f_l, a region growing algorithm is applied. The region growing algorithm was originally proposed as a phase unwrapping algorithm. In our method, the initial frequency map for the region growing algorithm can be determined as the value of f_j that minimizes D_{local} where D_{local} takes the single minimum in the D_{local}-f_j plot. This defines a 'frequency determined' region.

[0025]   Alternatively, a specific ΔTE can be chosen for simplification. The TE of the first data set will be an integer multiple of ΔTE. For example, a $\Delta TE = 2.2$ ms for 1.5 T can be chosen and:

$$S_1 = (W' - F')\exp(i\phi)$$

$$S_2 = (W' + F')\exp(i2\phi)$$

$$S_2 / S_0 = \exp(i2\phi)$$

[0026]   The second step is to find the correct frequency f_l at each pixel in a 'frequency to-be-determined region' which abuts the 'frequency determined' region found in previous steps. Figure 3 illustrates the process used to select a correct local frequency f_l. The shadowed region denotes the 'frequency determined' region. At each pixel that borders on the shadowed region, the value of f_j chosen is that which creates a local minima in the D_{local}-f_j plot, and, is

the closest to the average local frequency of the neighboring pixels in the frequency determined region. In Fig.3, suppose that the frequency of the pixel with a circle inside is to be determined and that D_{local} of this pixel takes more than one local minima. The value of f_j at which D_{local} takes local minima and is the closest to the average local value in the nearby frequency determined region is selected as f_l for the pixel. The frequency determined region is thereby expanded so that the frequency field map can be created for the entire scanned object region.

[0027]   After the frequency field map is obtained, the deblurred water and fat images W and F are reconstructed based on the frequencies indicated in the frequency field map at each pixel location. Specifically, the water and fat images decomposed with the frequency f_l, i.e., $\overline{W}'_l$ and $\overline{F}'_l$, derived from Eqs. [7, 8], are demodulated with demodulation frequencies f_l and $f_l + f_{fat}$ to create the locally deblurred images W_l and F_l, respectively. The entirely deblurred water image W can be reconstructed by combining the deblurred regions of water images W_l from each local frequency, f_l, in the frequency field map. The entirely deblurred fat image F can be reconstructed in a similar fashion.

[0028]   To simplify the method described above, ΔTE can be chosen as τ, the time during which fat spins precess by 180° out of phase with respect to water spins. This condition provides for a more efficient determination of the frequency map, With this condition, the signals at each pixel in the reconstructed images (S_0, S_1 and S_2) from these data sets can be expressed as:

$$S_0 = W' + F' \qquad\qquad\qquad [1a]$$

$$S_1 = (W' - F')\exp(i\phi) \qquad\qquad\qquad [2a]$$

$$S_2 = (W' + F')\exp(i2\phi) \qquad\qquad\qquad [3a]$$

where W' represent water signals blurred by local B_0 inhomogeneity off-resonance frequency f(Hz), F' are fat signals blurred by local B_0 inhomogeneity and chemical-shift off-resonance frequencies $f + f_{fat}$ (Hz), and ϕ is the phase shift due to B_0 inhomogeneity off-resonance effects during ΔTE. (The term f_{fat} can also be referred to as f_{shift} or f_s for chemical species other than fat) That is:

$$\phi = 2\ \pi\ f \cdot \Delta TE = 2\pi f \cdot \tau. \qquad\qquad\qquad [4a]$$

[0029]   Local off-resonance frequencies are determined. 2ϕ is obtained as:

$$2\phi = Arg(S_2 / S_0). \qquad\qquad\qquad [5a]$$

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[0030]   Even though signals blur into neighboring voxels due to the local off-resonance effects in the spiral image, from assumption (i), 2ϕ in Eq.[5a] gives the phase shift due to the true local B_0 inhomogeneity off-resonance frequency f at each pixel. Phase unwrapping is then performed to obtain the correct ϕ at each pixel using the region growing method with a manually selected seed point as described above. f can be successively determined from Eq.[4a].

[0031]   Water-fat signal decomposition is performed at each pixel based on the determined frequency map. From Eqs.[1a-3a], one obtains:

$$W' = ((S_0 + S_2 \exp(-i2\phi))/2 + S_1 \exp(-i\phi))/2 , \qquad [6]$$

$$F' = ((S_0 + S_2 \exp(-i2\phi))/2 - S_1 \exp(-i\phi))/2 . \qquad [7]$$

[0032]   De-blurring needs to be performed on the W' and F' images. This is achieved through the use of the frequency-segmented off-resonance correction method. This method reconstructs several images using different demodulation frequencies and selects the most de-blurred region from the stack of reconstructed images under the guidance of a frequency map. The demodulation frequencies used to de-blur W' are those given by the frequency map. The demodulation frequencies used to de-blur F' are the sum of the chemical-shift off-resonance frequency and the local frequencies given by the frequency map. The use of multiple demodulation frequencies enables de-blurred water and fat images, W and F to be reconstructed.

Spiral 2PD technique

[0033]   Although the spiral 3PD technique can achieve water-fat separation with off-resonance deblurring, the scan time is prolonged since three data sets are acquired. Here, a newly developed 2PD technique for spiral trajectories is described.

[0034]   In the spiral 2PD technique, as shown in Fig.4, the TE's of the first and second data acquisitions are $n\tau$ and $(n+1)\tau$, respectively, where n is a positive integer and τ is the time during which fat spins precess by 180° out of phase with respect to water spins.

[0035]   The signals at each pixel in the reconstructed images (S_0 and S_1) from these data sets can be expressed as:

$$S_0 = W' + F', \qquad [11]$$

$$S_1 = (W' - F') \exp(i\phi), \qquad [12]$$

where the definitions of W' and F' are the same as in the spiral 3PD technique, and ϕ is the phase shift due to B_0 inhomogeneity off-resonance frequency f (Hz) during τ (s). That is,

$$\phi = 2\pi f \cdot \tau .$$ [13]

Eq. [12] can be obtained by simply substituting $\exp(i\phi_{fat}) = -1$ in Eq. [2].

[0036]   Since it can be assumed that an RF pulse tip angle into the transverse plane is the same for both water and fat spins in each voxel, water and fat magnetization vectors in the transverse plane should be aligned with each other at the onset of the spiral gradient when TE is an even-integer multiple of τ and they are in the opposed phase when TE is an odd-integer multiple of τ (Fig.5). In other words, if W' and F' are deblurred by k-space data demodulation with the correct local off-resonance frequencies (the water and fat images obtained this way are defined as W and F, respectively), the orientation of the two vectors W and F will be identical when TE is an even-integer multiple of τ, and they will be opposite when TE is an odd-integer multiple of τ.

[0037]   In Fig. 5, the long and short arrows represent the water and fat magnetization vectors, respectively. ϕ_0 is the RF penetration angle. ϕ is the precession angle for the water magnetization during TE. **(a)** When TE is an even-integer multiple of τ, the water and fat magnetization vectors are aligned with each other at the onset of the spiral. **(b)** When TE is an odd-integer multiple of τ, the water and fat magnetization vectors are in the opposed phase at the onset of the spiral.

[0038]   For water-fat signal decomposition, as was done in the spiral 3PD technique, several predetermined demodulation frequencies f_j (Hz) are substituted into Eqs. [11,12]. W' and F' are solved for each demodulation frequency f_j (defined as W_j' and F_j', respectively.):

$$W_j' = \frac{S_0 \exp(i\phi_j) + S_1}{2\exp(i\phi_j)} ,$$ [14]

$$F_j' = \frac{S_0 \exp(i\phi_j) - S_1}{2\exp(i\phi_j)} ,$$ [15]

where $\phi_j = 2\pi f_j \cdot \tau$.

[0039]   The deblurred water and fat images W_j and F_j can be obtained after k-space data demodulation with the demodulation frequencies f_j and $f_j + f_{fat}$ for W_j' and F_j', respectively. To determine the correct B_0 inhomogeneity off-resonance frequency at each

pixel, the orientations of two vectors W_j and F_j are compared. When n is even (odd), the value of f_j that makes two vectors W_j and F_j aligned (opposed) to each other is selected as the correct local off-resonance frequency (the correct frequency is defined as f_l). As is evident, this process of local off-resonance frequency determination simultaneously reconstructs the final deblurred water and fat images, W and F.

[0040]   In practice, since some voxels contain predominantly either only water or fat spins, the vector alignment property described above is difficult to use. Hence, the following quantity is measured:

$$\Phi_j = 2 \cdot Arg\left(\frac{W_j + F_j}{W_j - F_j}\right) \qquad [16]$$

The absolute value of this quantity is minimized when the two vectors W_j and F_j are aligned/opposed or when either W_j or F_j predominantly exists. The similar concept was taken advantage of in an earlier rectilinear 2PD technique.

[0041]   As explained in the spiral 3PD technique, it is difficult to determine the correct frequency in image regions with low SNR. This is also true with the spiral 2PD technique. Therefore, in our algorithm, we first select the pixels of which the absolute values of Φ_j do not take sufficiently small values at any j. It is considered that the SNR of these pixels are low. Their frequencies are not evaluated in the following algorithm but are interpolated afterward based on the determined frequencies in their vicinity.

[0042]   After the 'frequencies to be evaluated' regions are determined, a similar algorithm to the spiral 3PD technique is used to reduce the errors in frequency evaluation: The summation of $\exp(i\Phi_j)$ within a small window centered on each pixel is measured and the real part of this quantity is extracted:

$$P_{local} = \mathrm{Re}(\sum_{window} \exp(i\Phi_j)) \qquad [17]$$

Note that the summation in Eq. [17] is a complex sum. P_{local} is expected to be maximized when $j = l$. However, since Φ_j often shows periodic-like patterns with j, even in the sufficiently high SNR regions, a plot of P_{local} -f_j often has more than one peak with their magnitudes close to one another. In our algorithm, all the values of f_j at which P_{local} takes local maxima in the P_{local}-f_j plot, are first chosen at every pixel (these f_j are defined as f_p). Then the region growing algorithm is performed to select the correct frequency f_l in a manner

similar to the spiral 3PD technique. In other words, of all the values of f_p, the one selected is that which is the closest to the average local frequency of the neighboring pixels in the frequency determined region. Unlike the spiral 3PD technique, the region growing algorithm starts with a manually selected single seed point in the spiral 2PD technique.

Algorithms for 2PD and 3PD techniques with multi-coil data sets

[0043]   Multi-element surface coils are often used to obtain images with higher SNR than would be achieved with a single larger coil. Each surface coil usually has a small region of signal sensitivity. Thus the image reconstructed from each set of individual coil data, shows non-uniform signal intensity over an FOV. The B_0 inhomogeneity frequency map derived from an individual coil may not be accurate for the region where the image SNR is low. This subsection describes how to apply the 3PD and 2PD spiral reconstruction algorithms described previously when data are acquired from multi-element surface coils. D_{local} in Eq.[10] is redefined as

$$D_{local} = \sum_{m}^{n} D_{local} c_m \qquad [18]$$

to extend the spiral 3PD algorithm from a single data set to one for multi-coil acquisitions. Here, n is the total number of coils and $D_{local}c_m$ is D_{local} defined in Eq. [10] of the m-th coil data. The frequency field map can be determined by applying the same algorithm described in the previous subsection of the spiral 3PD technique using D_{local} as defined in Eq. [18].

[0044]   For the spiral 2PD technique, at each demodulation frequency f_j, the quantity expressed as Eq. [16] is calculated for each coil data. They are combined at each pixel, weighted by the signal intensities of the reconstructed images. Hence, Φ_j is redefined as:

$$\Phi_j = Arg(\sum_{m}^{n} \left(\left| W_j c_m \right| + \left| F_j c_m \right| \right) \cdot \exp(i \cdot 2Arg\left(\frac{W_j c_m + F_j c_m}{W_j c_m - F_j c_m} \right))) \qquad [19]$$

where n is the total number of coils, $W_j c_m$ and $F_j c_m$ are the water and fat images reconstructed from the m-th coil data with the predetermined demodulation frequency f_j. P_{local} is computed from Φ_j defined in Eq. [19] using the same algorithm as explained in the previous section of the spiral 2PD technique. The method to determine the frequency field map from the newly defined P_{local} is also the same.

One-acquisition spiral Dixon techniques using variable density spiral trajectories

[0045]   Ideally, only one acquisition would be needed for fat/water decomposition. An efficient spiral off-resonance correction method with only one acquisition has been proposed. This method is called 'off-resonance correction using variable density spirals (ORC-VDS)'. In this method, odd- and even-numbered spiral interleaves have slightly different TE's and the central portion of k-space is oversampled using variable density spiral trajectories. A B_0 inhomogeneity field map can be calculated by taking the phase difference between the two low resolution images reconstructed from the data of odd- and even-numbered spiral interleaves.

[0046]   The extensions of this method to the spiral 3PD and 2PD techniques are quite straightforward. Figure 6 shows the spiral trajectories that oversample the inner regions of k-space with three times (a) and twice (b) higher sampling densities than the outer parts.

[0047]   In Fig.6a, the solid, dashed, and dotted spiral trajectories have three different TE's with their TE differences constant. In Fig.6b, the solid and dashed spiral trajectories have different TE's with their TE difference equal to τ. In both cases, off-resonance frequency field maps can be derived from the low spatial frequency data using the same algorithms as the spiral 3PD and 2PD techniques described above. It can be expected that these spiral acquisition schemes make it possible to perform the algorithms of spiral 3PD and 2PD techniques with only one acquisition. The Dixon techniques taking advantage of the sampling schemes shown in Fig.6a and b will be referred to as 'variable density spiral 3PD (VDS-3PD) technique' and 'variable density spiral 2PD (VDS-2PD) technique' from this point on. A description of the reconstruction algorithms of VDS-3PD/2PD techniques follows.

[0048]   In both the VDS-3PD and VDS-2PD techniques, a frequency field map is derived from only low spatial frequency data using the spiral 3PD and 2PD algorithms, respectively. Water-fat decomposition and k-space data demodulation are performed for the low spatial frequency data based on the frequencies indicated in the frequency field map. High spatial frequency data are also demodulated with the demodulation frequency indicated in the frequency field map and will be added to the demodulated low spatial frequency data.

[0049]   In the VDS-3PD technique, the high frequency data of three different TE's (they are defined as Sh_0, Sh_1 and Sh_2) are combined so that their phases are consistent with one another. In other words, when the demodulation frequency is f_l (Hz), the high spatial frequency data of the three TE's to be added to the water image, are combined as (it is defined as Shw):

$$Shw = Sh_0 + Sh_1 \exp(-i2\pi f_l \Delta TE) + Sh_2 \exp(-i2\pi f_l \cdot 2\Delta TE),\qquad [20]$$

and those that will be added to the fat image are combined as (it is defined as Shf):

$$Shf = Sh_0 + Sh_1 \exp(-i2\pi(f_l + f_{fat})\Delta TE) + Sh_2 \exp(-i2\pi(f_l + f_{fat}) \cdot 2\Delta TE).\qquad [21]$$

[0050]   Similarly, in the VDS-2PD technique, the high frequency data of two TE's (Sh_0 and Sh_1) to be added to the water image are combined as:

$$Shw = Sh_0 + Sh_1 \exp(-i2\pi f_l \tau),\qquad [22]$$

and those to be added to the fat image are combined as:

$$Shf = Sh_0 - Sh_1 \exp(-i2\pi f_l \tau).\qquad [23]$$

[0051]   In both VDS-3PD/2PD techniques, Shw and Shf are demodulated with the demodulation frequencies f_l and $f_l + f_{fat}$, respectively. These demodulated high frequency data are added to the low frequency water and fat images that are already demodulated by the same frequencies f_l and $f_l + f_{fat}$, respectively. As described above, f_{fat} can be referred to as f_{shift} or f_s for applicable chemical species other than fat.

[0052]   Both the spiral 3PD and 2PD techniques were implemented for in-vivo imaging experiments. All experiments were performed using a 1.5-Tesla Siemens Sonata scanner (Siemens Medical Solutions, Erlangen, Germany). In these experiments, axial brain and pelvis images were acquired from a healthy volunteer using a quadrature head coil and four-element phased array surface coils, respectively. All procedures were done under an institutional review board approved protocol for volunteer scanning.

[0053]   The following sequence parameters were the same for all the spiral sequences used in the experiments: for the brain image experiments, there were 20 spiral interleaves, FOV 240x240mm, slice thickness 10mm, flip angle 13°, spiral readout time 16ms, and TR 25ms. For the pelvis imaging experiments, there were 20 spiral interleaves, FOV 390x390mm slice thickness 10mm, flip angle 13°, spiral readout time 15ms, and TR 25ms.

[0054]   For the spiral 3PD technique, TE's were set to 3.0(1st)/4.5(2nd)/6.0ms(3rd) in both the brain and pelvis imaging experiments. ΔTE was set to 1.5ms as the maximum SNR is attained when $\phi_{fat} = 120°$, as described in ref.18.

[0055]   For the spiral 2PD technique, TE's were set to 2.2(1st)/4.4ms(2nd) in both the brain and pelvis imaging experiments.

[0056]   The normal spiral sequences with SPSP pulses were also implemented for comparison. 1-4-6-4-1 binomial pulses were used for excitation. The total flip angle for on-

resonance spins was 16°. Two acquisitions were performed for off-resonance correction. TR was 33ms and TE's were set to 6.0/7.5(ms) in both the brain and pelvis imaging experiments.

[0057] The VDS-3PD technique was implemented for the axial pelvis image. The image was scanned from the same volunteer using four-element surface coils. The sequence parameters were: 18 interleaved spirals, TE 3.0/4.5/6.0ms (each TE was shared by 6 interleaves), TR 25ms, flip angle 13°, FOV 390mm x 390mm, slice thickness 10mm, and the radius of the over-sampled region was 40% of k_{max}.

[0058] For reconstruction of the brain images, k-space data re-gridding was performed to a Cartesian grid. The modified Block Uniform Resampling (BURS) algorithm was used for k-space re-gridding. For reconstruction of the pelvis images, the matrix rescaling algorithm (the equivalent algorithm was also proposed as 'next-neighbor re-gridding') was used to facilitate reconstruction of the multiple k-space data sets. For both water and fat images, the image reconstructed from each coil data was combined using the sum-of-squared method.

[0059] The predetermined demodulation frequencies are ranged from −200Hz to +200Hz with the frequency resolution 10Hz (i.e., 41 demodulation frequencies in total) in all image reconstructions. The window sizes to compute D_{local} were set to 9x9 pixels and 5x5 pixels for the brain and pelvis image reconstructions, respectively. The window sizes to compute P_{local} were set to 9x9 pixels and 5x5 pixels for the brain and pelvis image reconstructions, respectively.

[0060] Both spiral 3PD and 2PD techniques successfully perform off-resonance correction with water-fat signal decomposition. As mentioned, one of the main advantages of the Dixon technique is that uniform fat suppression can be achieved across an FOV in the presence of B_0 inhomogeneity. Both the spiral 3PD and 2PD techniques lead not only to uniform fat suppression but they avoid unwanted water signal suppression when B_0 inhomogeneity exists.

[0061] Undesirable water signal suppression could be reduced by the use of SPSP pulses with a sharper transition band between the water and fat frequencies. However, such SPSP pulses usually take a relatively long time for excitation. As mentioned, the time duration of SPSP pulses is sometimes equivalent to or may be longer than the spiral readout time. Therefore, the minimum possible TE and TR are determined by the lengths of the SPSP pulses. On the other hand, since normal small flip angle RF pulses are used and hence short TE's can be set in both the spiral 3PD and 2PD techniques, these techniques can provide a

way to reduce the scan time in spiral imaging.

[0062] A five-pulse binomial scheme was used for spatial-spectral excitation in experiments. It was about 9ms in duration. The length of a SPSP pulse in other previous studies using spiral trajectories was about 16ms. The spiral 3PD and 2PD techniques employ normal small flip angle RF pulses and the excitation usually takes only 2-3ms for each TR. If short TE's (2~4ms) are used in the newly proposed techniques, TR can be possibly reduced by approximately 10ms from the spiral acquisitions with SPSP pulses. For example, total acquisition time may be reduced by about 200ms (or almost half) in 20 interleaved spiral trajectories. The newly proposed techniques can be used to improve temporal resolution in some applications of spiral imaging, such as BOLD imaging and dynamic breast imaging.

[0063] As the spiral 2PD technique achieves almost the same performance as the spiral 3PD technique, it is suggested that the spiral 2PD technique be used if a shorter total acquisition time is required. However, in addition to better image SNR, the spiral 3PD technique has a couple of advantages over the spiral 2PD technique. When a frequency field map is determined, no Fast Fourier Transform (FFT) needs to be performed in the spiral 3PD technique; this can be understood from Eq. [9]. On the other hand, a number of FFTs are required in the spiral 2PD technique. Specifically, at each predetermined demodulation frequency f_j, two FFTs (to demodulate W_j' and F_j') are needed and hence the total number of FFT required is twice the total number of predetermined frequencies. As mentioned, some of these FFTs may be unnecessary to reconstruct the final deblurred images W and F. Hence, the spiral 3PD technique is computationally more efficient than the spiral 2PD technique since the FFT is the most computationally intensive part in our algorithm. Another advantage of the spiral 3PD technique over the spiral 2PD technique is that the initial frequency field map can be determined without manual seed point selection when the frequency field map is determined using the region growing algorithm. As explained above, the initial frequency field map consists of the pixels of which D_{local}-f_j plots have single minimum. Alternately, the spiral 2PD technique needs manual seed point selection to start the region growing algorithm when a frequency field map is determined as is also the case with the rectilinear 2PD technique.

VDS Dixon techniques

[0064]   In the conventional spiral acquisition method with SPSP pulses, two data sets with different TE's usually need to be acquired to correct for off-resonance blurring artifacts. The necessity of two data sets diminishes the advantage of spiral imaging as a fast acquisition method. When non-negligible motion is involved between the first scan and the subsequent scan, the off-resonance correction algorithm may fail in spiral imaging because of motion-dependent misregistration between the two images. Similarly, accurate water-fat decomposition may not be achieved in the Dixon technique if there is motion-dependent misregistration among the reconstructed images with different TE's. VDS-3PD/2PD techniques have overcome these drawbacks.

[0065]   As is evident in the algorithms of VDS-3PD/2PD techniques described above, since high frequency data can not be separated into water and fat signals, when the combined high frequency data of water S_{hw} (Eqs.[20, 22]) are added to the low resolution water image, fat signals in the high frequency data are also added to the low resolution water image. However, as evident from the difference between Eqs. [20 and 21] and the difference between Eqs. [22 and 23], the phases of fat signals in the high frequency data of different TE's are not consistent with one another when water signals in the high frequency data are phase-consistent. Moreover, when the water image is reconstructed, the fat signals in the high frequency data are demodulated not by their demodulation frequency $f_l + f_{fat}$ but by the demodulation frequency of water signals f_l. Therefore, the high frequency components of the fat signals are smeared out in the water image. As the total signal amounts of the high frequency components are usually quite small compared with those of the low frequency components, the artifacts due to high frequency components of the fat signals are inconsequential in the water image. Similarly, since water signals in the high frequency data are spread out in the fat image, there are usually no apparent artifacts in the fat image caused by the high spatial frequency water signals.

[0066]   The spiral 3PD and 2PD techniques proposed here can achieve not only water-fat signal decomposition but also off-resonance blurring artifact correction. The SPSP pulses commonly used in spiral imaging may not lead to uniform fat suppression and they may also yield undesirable water signal suppression in the presence of B_0 inhomogeneity. Furthermore, they usually require a long time for excitation. These disadvantages of SPSP pulses can be overcome by the techniques we have proposed which provides excellent performance as well as reduced acquisition time. Although they require additional computational costs to the conventional spiral off-resonance correction method, faster data acquisition is possible than

in conventional spiral acquisitions that use SPSP pulses. One-acquisition spiral Dixon techniques using variable density spiral trajectories have also been shown to be simple extensions of the spiral 3PD and 2PD techniques, thereby avoiding the need for multiple separate acquisitions. The spiral Dixon techniques proposed here offer new and alternative approaches to achieve effective fat signal suppression with reduced scan time.